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Bissbort et al.

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(54) **HYDRAULIC SUSPENSION FOR VEHICLE AND MULTI-FUNCTIONAL PROPORTIONAL CONTROL VALVE FOR THE SAME**

(58) **Field of Classification Search**
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F15B 11/165; F15B 11/167
See application file for complete search history.

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(57) **ABSTRACT**

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A hydraulic suspension system includes a suspension cylinder, a pump, and a control valve therebetween. The control valve includes a spool reciprocally movable between a pump flow position and a tank flow position in which a control port of the control valve is in communication with a pump and a tank, respectively. A piloted logic element in fluid communication with and interposed between the control valve and the suspension cylinder is selectively movable between a through-flow position in which fluid can flow in either direction between a chamber of the suspension cylinder and the control port of the control valve and a blocked position in which fluid is prevented from flowing in or out of the chamber of the suspension cylinder. The logic element is biased to the blocking position, moving to the through-flow position when subjected to a crack pressure delivered from the control port of the control valve.

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F15B 1/04 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC **F15B 1/04** (2013.01); **B60G 17/056** (2013.01); **F04B 53/10** (2013.01); **F15B 1/021** (2013.01);
(Continued)

18 Claims, 10 Drawing Sheets

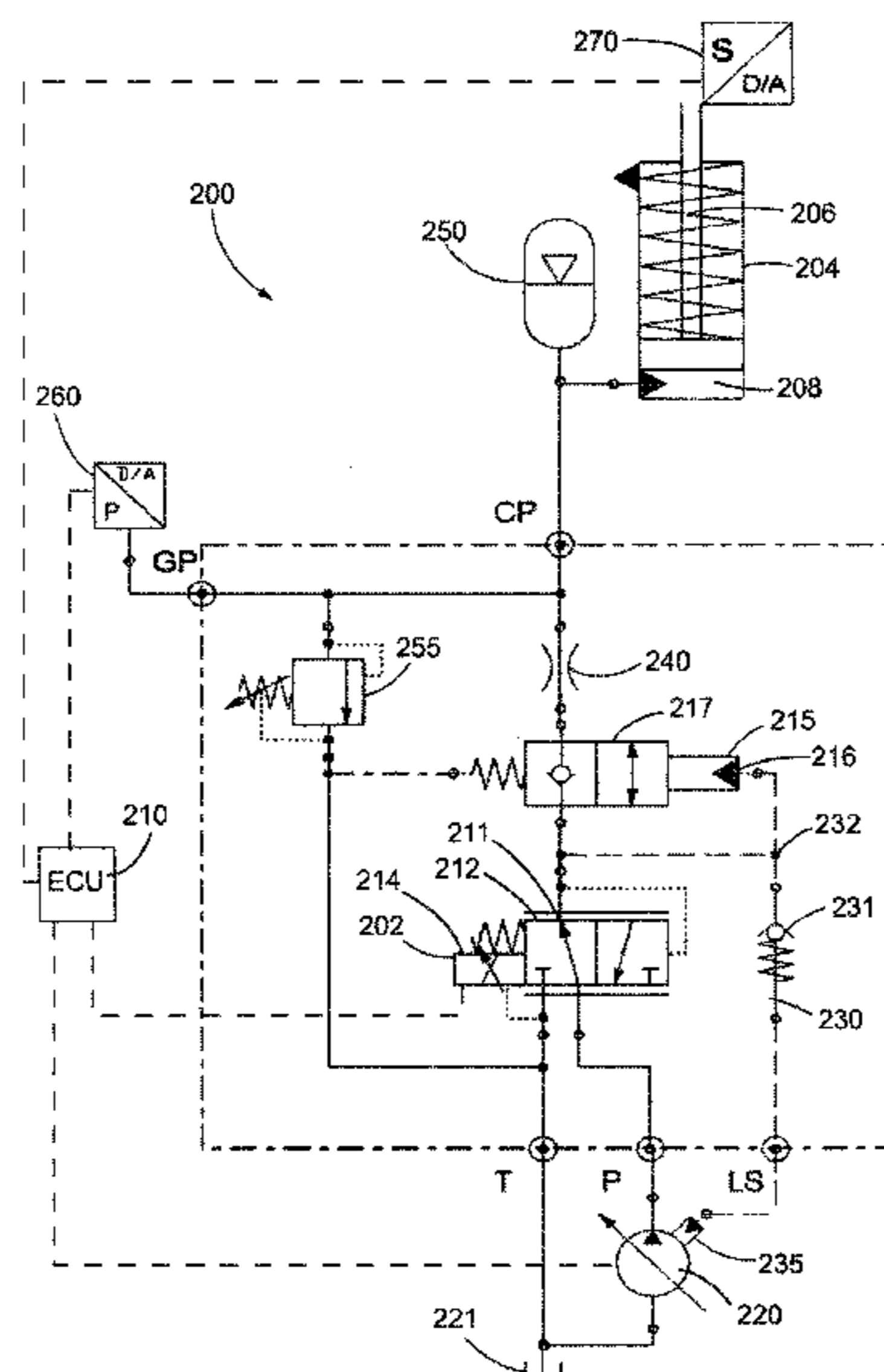
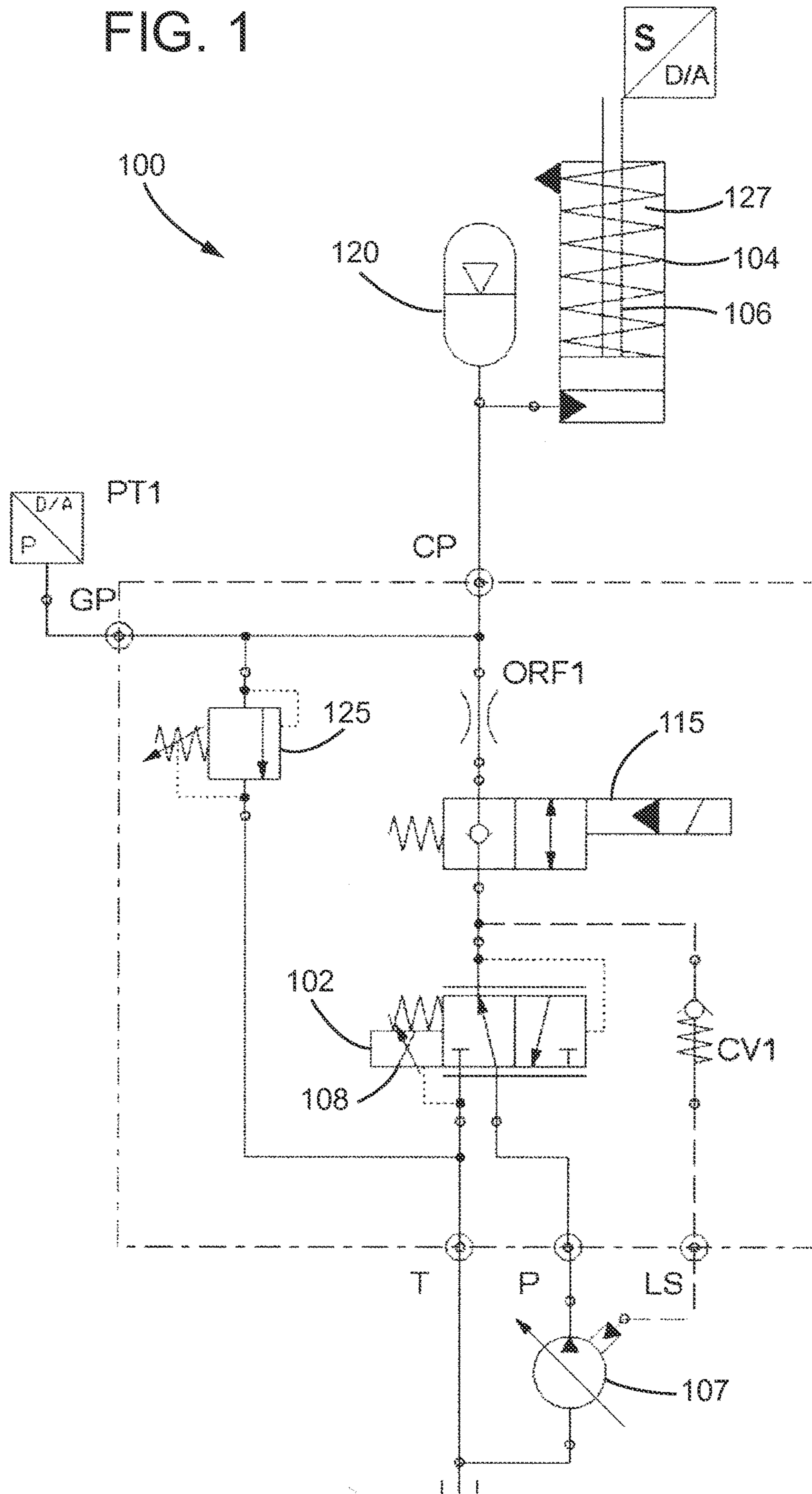


FIG. 1



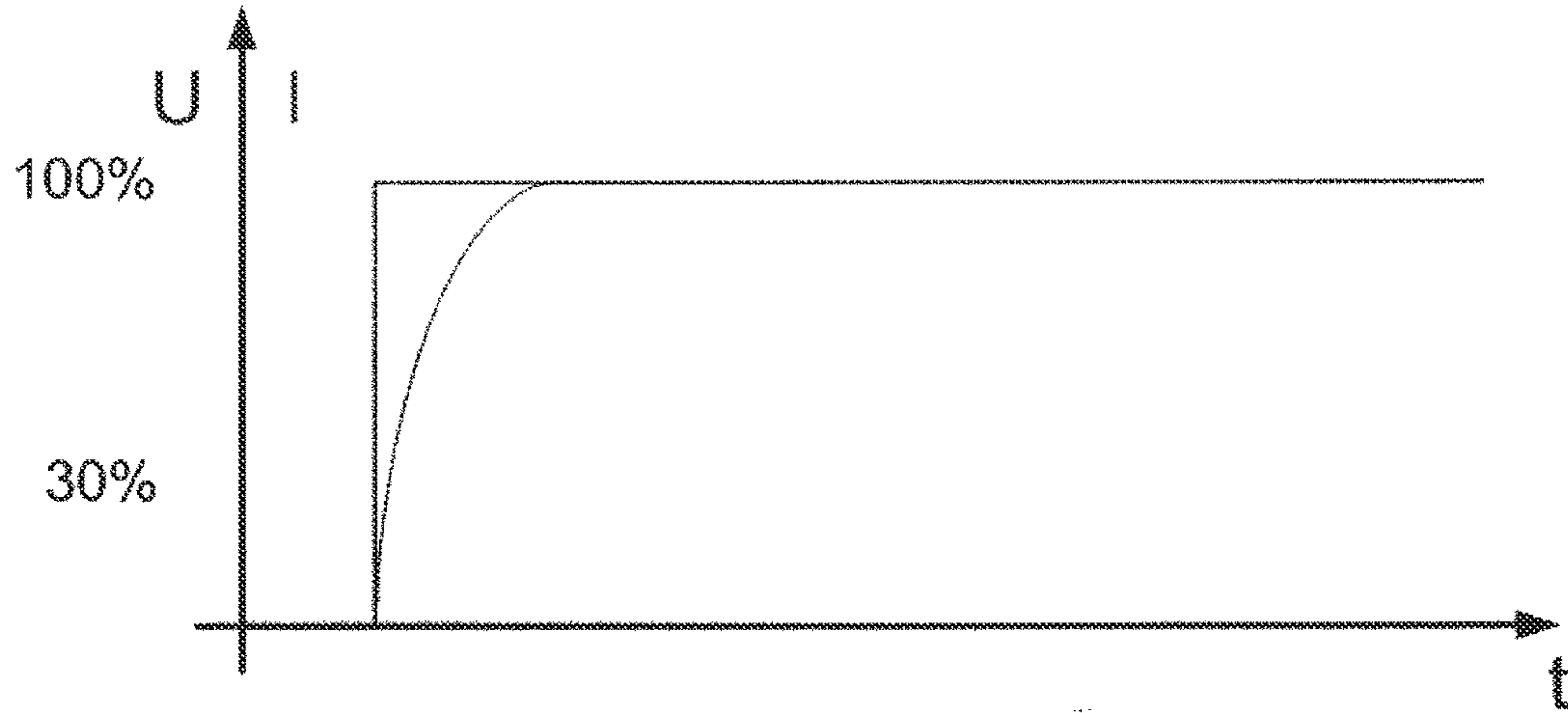


FIG. 3

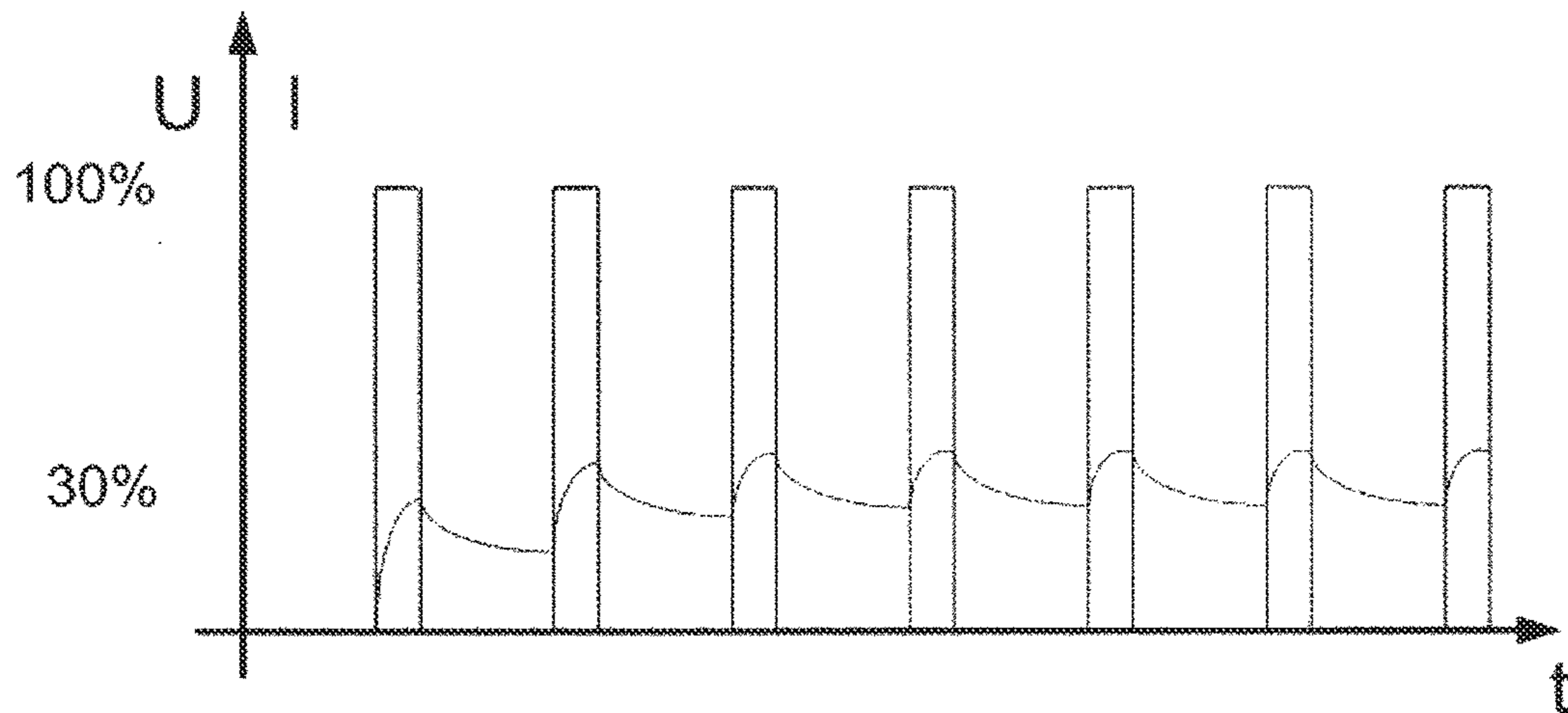


FIG. 4

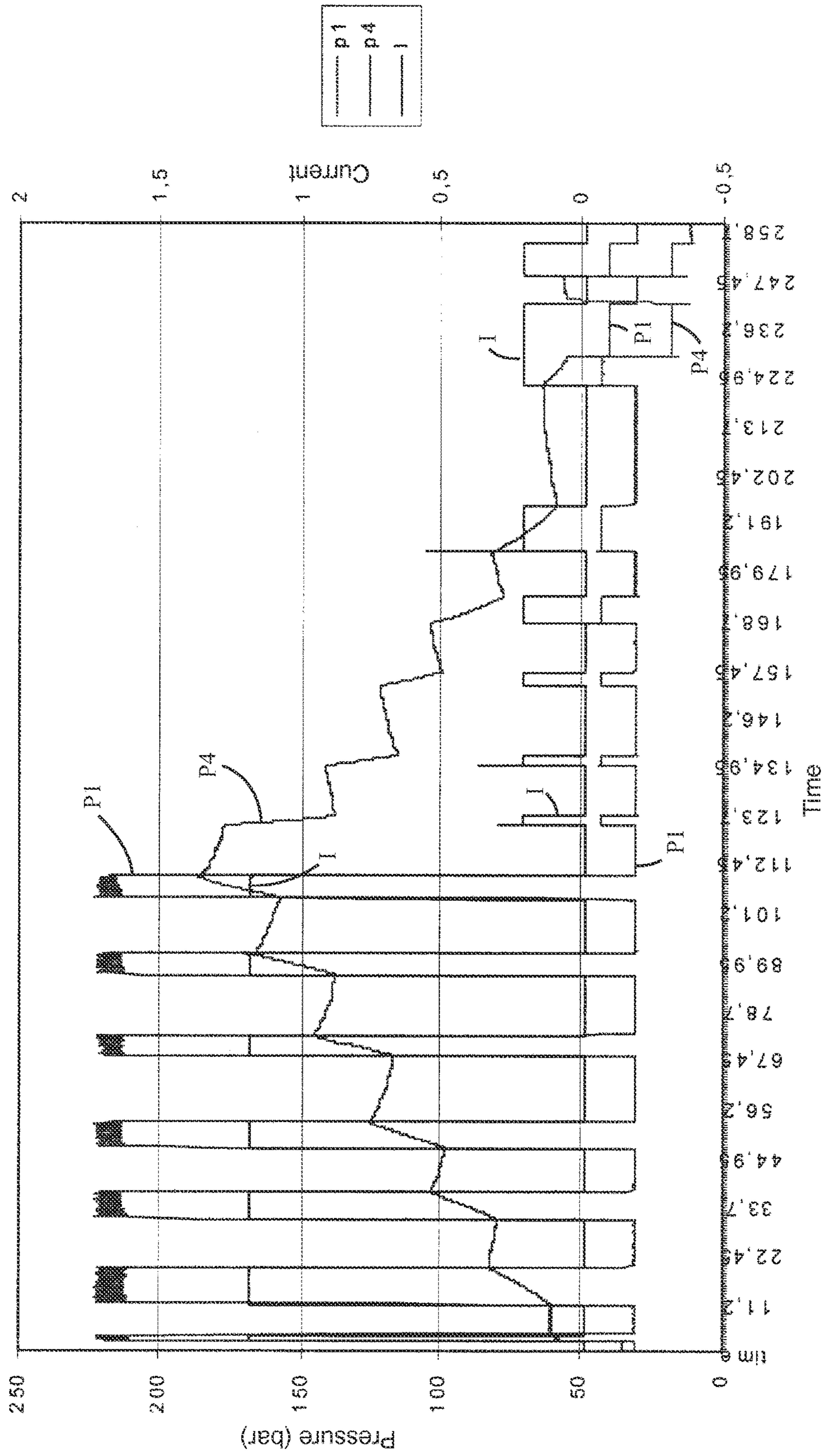
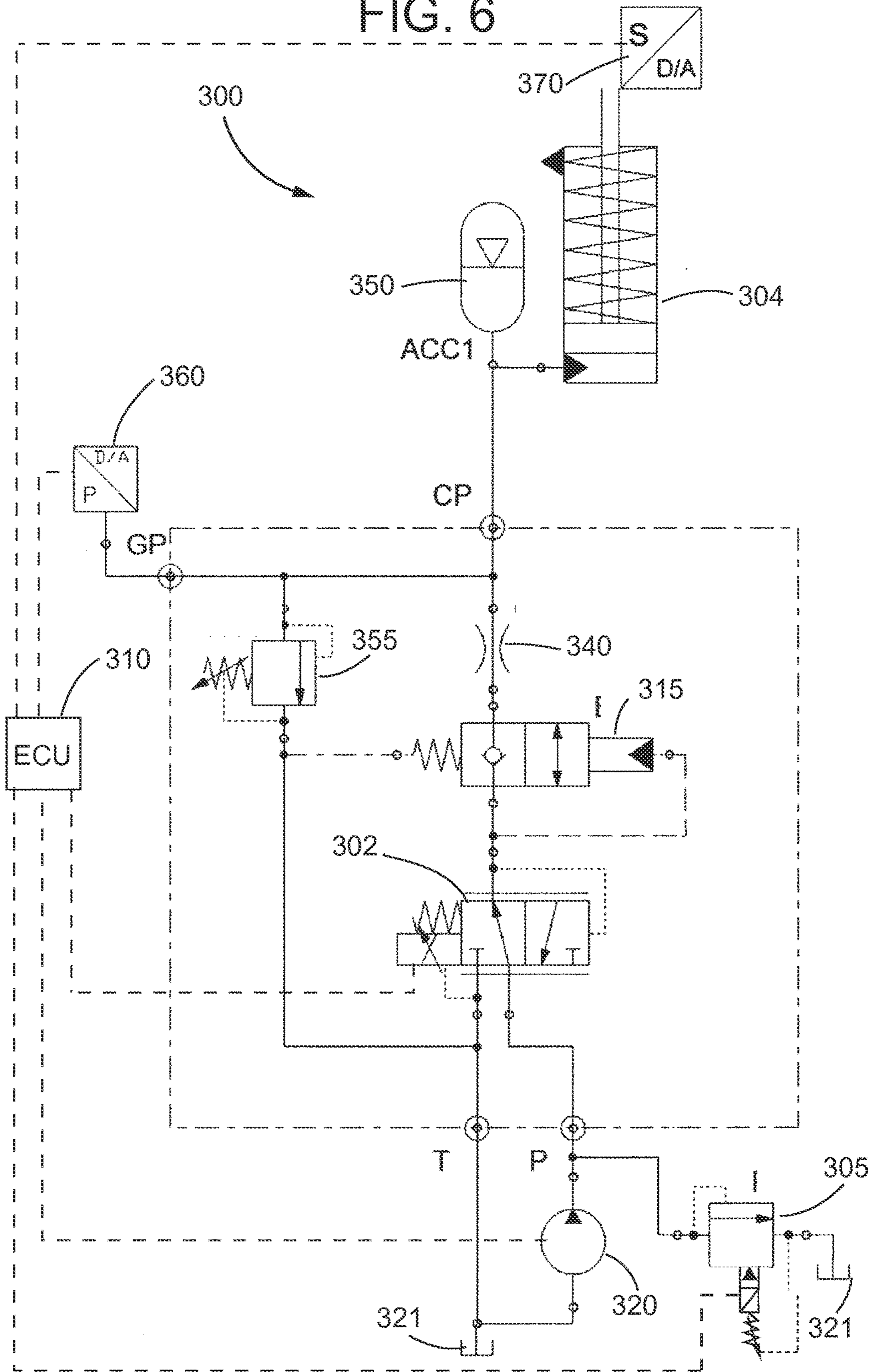


FIG. 5

FIG. 6



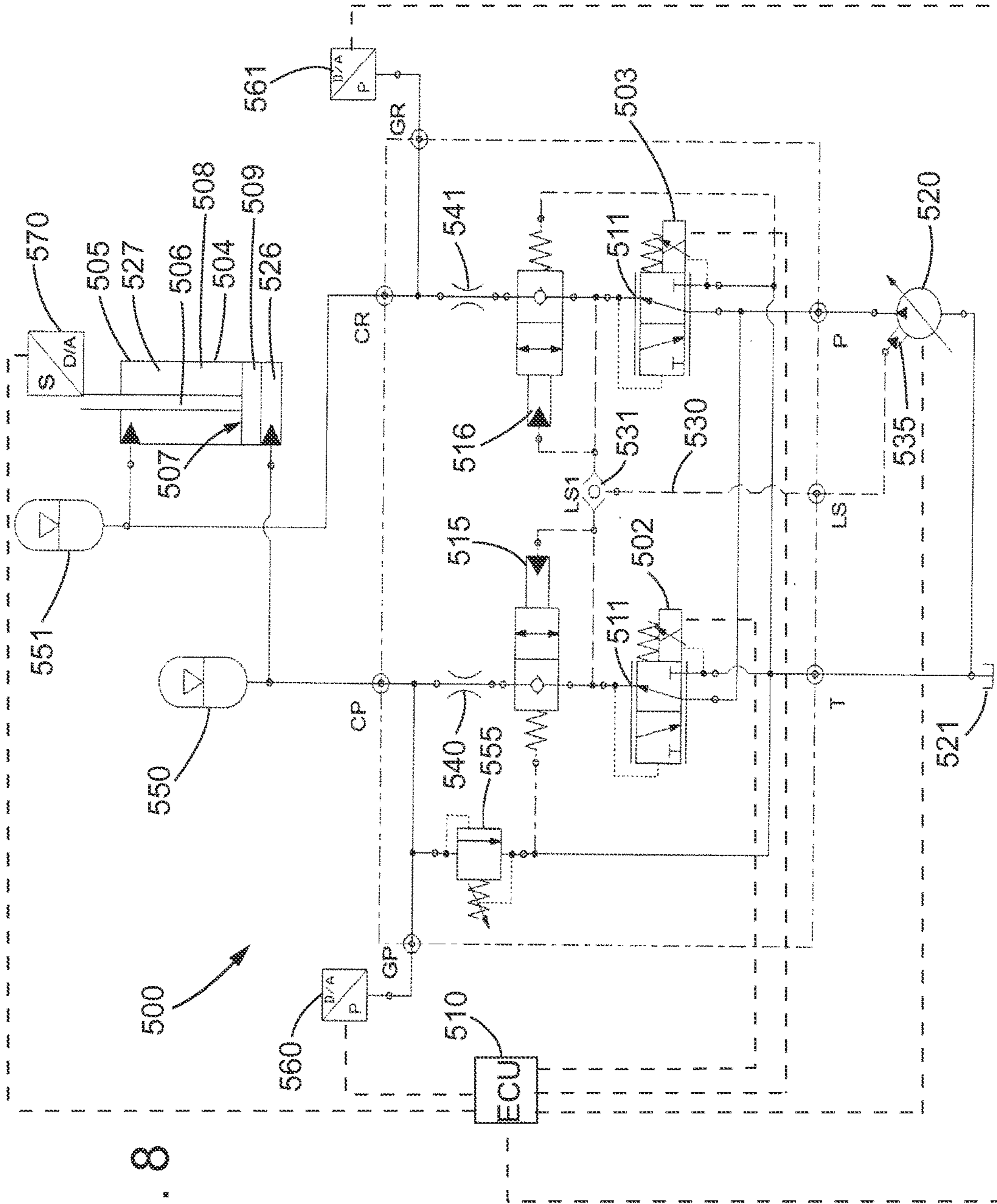


FIG. 8

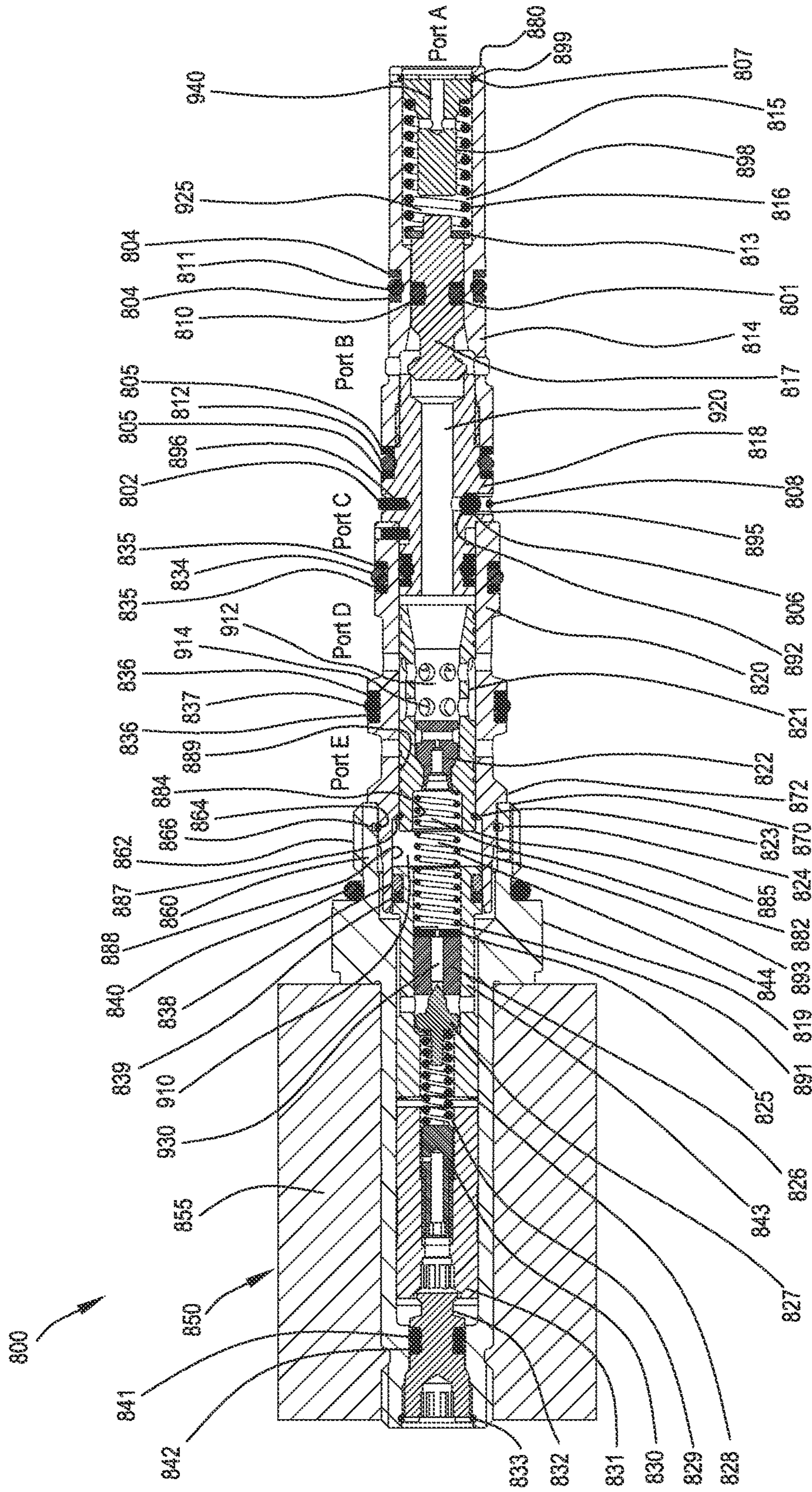


FIG. 11

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**HYDRAULIC SUSPENSION FOR VEHICLE
AND MULTI-FUNCTIONAL PROPORTIONAL
CONTROL VALVE FOR THE SAME**

CROSS-REFERENCE TO RELATED
APPLICATIONS

This patent application claims the benefit of priority to U.S. Provisional Patent Application No. 61/776,505, filed on Mar. 11, 2013, and entitled "Hydraulic Suspension System for Vehicles and Multi-Functional Proportional Control Valve for the Same," which is incorporated in its entirety herein by this reference.

TECHNICAL FIELD

This patent disclosure relates generally to a hydraulic suspension system and, more particularly, to a hydraulic suspension system, (e.g., axle suspension, single wheel suspension, cabin suspension) where a combination of valves is used to control the suspension cylinder(s) to the nominal position when the load on the system has changed or to charge or discharge the rod side pressure in a double-acting system to thereby adjust the spring curve.

BACKGROUND

In conventional commercial systems, at least two solenoid valves are used to control a single-acting cylinder, and at least three solenoid valves (see, e.g., U.S. Pat. No. 8,096,568 B2 to Huth) or four solenoid valves (see, e.g., U.S. Patent Application Publication No. US2005/0050886 A1 to Bauer et al.) are used to control a double-acting system independently at the same time. In other known systems, three solenoid valves in combination with one proportional pressure-reducing valve are used to control a double-acting system independently at the same time (see, e.g., U.S. Pat. No. 7,219,779 B2 to Wolfgang and U.S. Pat. No. 7,048,280 B2 to Brandenburger). Another known system uses two proportional and two solenoid valves to control a double-acting system independently (see, e.g., U.S. Pat. No. 7,753,385 B2 to Bitter).

Some existing systems are equipped with additional, non-integral check valves for load sensing/piloting. Additionally, check valves or low-leakage solenoid-operated valves are included in some conventional systems to hold the mechanical system rigid when power is not applied.

It will be appreciated that this background description has been created by the inventors to aid the reader, and is not to be taken as an indication that any of the indicated problems were themselves appreciated in the art. While the described principles can, in some aspects and embodiments, alleviate the problems inherent in other systems, it will be appreciated that the scope of the protected innovation is defined by the attached claims, and not by the ability of any disclosed feature to solve any specific problem noted herein.

SUMMARY OF THE DISCLOSURE

The present disclosure, in one aspect, is directed to embodiments of a hydraulic circuit configured to reduce the complexity and cost of the combination of valves used in a suspension system while maintaining equivalent or improved performance compared to existing solutions. In addition, the present disclosure, in another aspect, is directed to embodiments of a multi-function control valve adapted for use with embodiments of a hydraulic circuit where a

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single-acting cylinder can be controlled (extended and retracted) with only one control valve. In another aspect, embodiments of a multi-function control valve are included in a hydraulic circuit in which only two control valves are needed to allow independent control from the piston and rod side (extended and retracted or charging and discharging) of a double-acting system.

In one embodiment, a hydraulic suspension system includes a controller, a pump, a tank, a suspension cylinder, a proportional pressure-reducing/-relief control valve, and a logic element. The pump is adapted to provide a source of pressurized fluid, and the tank is adapted to hold a reservoir of fluid. The tank is in fluid communication with the pump. The suspension cylinder is in selective fluid communication with the pump. The suspension cylinder defines a chamber therein adapted to receive pressurized fluid.

The proportional pressure-reducing/-relief control valve is in electrical communication with the controller and in fluid communication with the pump. The control valve includes a spool reciprocally movable over a range of travel between at least a pump flow position in which the pump and a control port of the control valve are in fluid communication with each other and a tank flow position in which the tank and the control port of the control valve are in fluid communication with each other. The control valve is adapted such that the spool moves in response to a control signal received from the controller and the fluid pressure at the control port.

The logic element is in fluid communication with and interposed between the control valve and the suspension cylinder. The logic element includes a poppet selectively movable between a through-flow position in which fluid can flow in either direction between the chamber of the suspension cylinder and the control port of the control valve and a blocked position in which fluid is prevented from flowing out of the chamber of the suspension cylinder. The logic element is biased to the blocking position. The logic element is adapted to move from the blocking position to the through-flow position when a pressure at a fluid region upstream of the logic element poppet exceeds a predetermined crack pressure. The fluid region upstream of the logic element poppet is in fluid communication with the control port of the control valve.

In another aspect of the present disclosure, a multifunctional proportional control valve includes a control valve portion and a logic element portion in communication with the control valve portion. The control valve portion and the logic element portion are contained within a single cartridge arrangement.

The control valve portion includes a control valve cage and a hollow spool. The control valve cage defines a longitudinal interior passageway, a tank port, and a pump port. The tank and pump ports are in communication with the interior passageway. The spool defines a longitudinal spool passageway and a plurality of cross holes radially arranged about the spool. The cross holes are in communication with the spool passageway and the interior passageway of the control valve cage. The spool is disposed within the interior passageway of the control valve cage and reciprocally movable over a range of travel between a pump flow position in which the pump port of the control valve cage is open and the tank port of the control valve cage is closed and a tank flow position in which the tank port of the control valve cage is open and the pump port of the control valve cage is closed. The spool is biased to the pump flow position.

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The logic element portion includes a logic element cage and a logic element poppet. The logic element cage defines a longitudinal interior logic element passageway and a logic element port in communication with the logic element passageway. The logic element passageway is in communication with the spool passageway. The logic element poppet is disposed within the logic element passageway of the logic element cage and is reciprocally movable over a range of travel between a blocking position in which the logic element port of the logic element cage is closed and a logic element through-flow position in which the logic element port of the logic element cage is open. The logic element poppet is biased to the blocking position such that the logic element poppet remains in the blocking position until a pressure at least equal to a crack pressure is applied to the logic element poppet against the biasing force, thereby unseating the logic element poppet from the blocking position and moving the logic element poppet toward the through-flow position.

Further and alternative aspects and features of the disclosed principles will be appreciated from the following detailed description and the accompanying drawings. As will be appreciated, the hydraulic circuits, the multi-function control valves, and methods disclosed herein are capable of being carried out in other and different embodiments, and capable of being modified in various respects. Accordingly, it is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory only and do not restrict the scope of the appended claims.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

FIG. 1 is a schematic view of a hydraulic circuit.

FIG. 2 is a schematic view of an embodiment of a hydraulic circuit in accordance with principles of the present disclosure, illustrating a single-acting system.

FIG. 3 is a graph of an illustrative controller digital voltage output (U) and corresponding current (I) to control valve versus time (t) for a single-acting system in accordance with principles of the present disclosure, illustrating a controller output in a condition referred to as "on-high."

FIG. 4 is a graph of another illustrative controller digital voltage output (U) and corresponding current (I) to control valve versus time (t) for a single-acting system in accordance with principles of the present disclosure, illustrating a controller output in a condition referred to as "on-low."

FIG. 5 is a graph of illustrative valve settings versus time for a single-acting system in accordance with principles of the present disclosure, illustrating the control pressure between a proportional pressure-reducing/-relieving valve and a logic element valve, the pressure in a cylinder, and the current to the proportional pressure-reducing/-relieving valve over time.

FIG. 6 is a schematic view of an embodiment of a hydraulic circuit in accordance with principles of the present disclosure, illustrating a single-acting system with a constant pump.

FIG. 7 is a schematic view of another embodiment of a hydraulic circuit in accordance with principles of the present disclosure, illustrating a single-acting system with a one-way restriction orifice.

FIG. 8 is a schematic view of an embodiment of a hydraulic circuit in accordance with principles of the present disclosure, illustrating a double-acting system.

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FIG. 9 is a schematic view of an embodiment of a hydraulic circuit in accordance with principles of the present disclosure, illustrating a double-acting system with a pair of one-way restriction orifices.

FIG. 10 is a schematic view of another embodiment of a hydraulic circuit in accordance with principles of the present disclosure, illustrating a double-acting system with an embodiment of a multi-functional control valve constructed in accordance with principles of the present disclosure.

FIG. 11 is an elevational view, in cross section, of an embodiment of a multi-functional control valve constructed in accordance with principles of the present disclosure.

DETAILED DESCRIPTION

Embodiments of a hydraulic circuit constructed in accordance with principles of the present disclosure are adapted to control the position and/or the pressure of a suspension cylinder (e.g., axle suspension, single wheel suspension, cabin suspension). In embodiments of a hydraulic suspension system, a proportional pressure-reducing/-relieving valve is adapted to open and close a piloted logic element valve to control the cylinder pressure/position. Embodiments of a hydraulic suspension circuit constructed in accordance with principles of the present disclosure can have the same or similar functionality as conventional circuits, but with reduced complexity.

Embodiments of a control valve constructed in accordance with principles of the present disclosure combine the functionality of several valves into one cartridge that is used to control the suspension cylinders) to the nominal position/pressure when the load on the system has changed. In embodiments, a control valve constructed in accordance with principles of the present disclosure combines the functionality of multiple conventional valves in a hydraulic suspension system constructed in accordance with principles of the present disclosure into one valve. In embodiments, a proportional valve in combination with a control strategy following principles of the present disclosure reduces the number of components (e.g., valves, controller outputs, manifold size) which are needed to control a suspension system.

Following principles of the present disclosure, embodiments of a hydraulic suspension system can achieve similar functionality as conventional systems but with reduced cost and complexity. Cost can be reduced by reducing the number of components and wire connections relative to prior solutions. For example, in embodiments, the system can be equipped with a smaller/lower weight manifold relative to one used in a conventional system that will still provide the desired performance characteristics.

Embodiments of a hydraulic suspension system according to principles of the present disclosure can have improved reliability as a result of using a reduced number of valves and wire connections and a corresponding reduced number of controller outputs. For example, in embodiments, only one controller output and one coil are used for a single-acting system, and only two controller outputs and two coils are used for a double-acting system.

In embodiments, a hydraulic suspension system and a multi-functional control valve constructed in accordance with principles of the present disclosure can provide enhanced system performance in that proportional control can be provided, rather than simply an on/off condition. In embodiments, two digital control outputs with a third stage (off, on-low, on-high) can be used to control the hydraulic suspension system. In other embodiments, one digital con-

control output with one proportional output can be provided but without the need for a pressure transducer. In still other embodiments including one digital control output and one proportional output, pressure on a rod side of the suspension cylinder can be kept constant during the stroke of the piston assembly by using a level-control feature on the piston side.

In embodiments of a double-acting system following principles of the present disclosure, two proportional control outputs can be provided which can yield higher performance of the control algorithm (e.g., in combination with unidirectional restrictors or without restrictors). The speed of the level and the pressure control is adjustable. Independent control of the piston side (level control) and the rod side (pressure control) with two independent valves (charge and discharge at the same time) is possible. The pressure on the rod side can be adjusted to different settings to thereby produce different spring curves. This adjustment can be done related to several parameters, such as driving speed, axle load, drivers setting, etc. Systems constructed according to principles of the present disclosure can be used as an active suspension system (in special situations, for example, during braking or during acceleration).

In combination with two proportional outputs, the pressure can be controlled continuously with a multi-functional control valve constructed according to principles of the present disclosure to a desired value. A multi-functional control valve constructed according to principles of the present disclosure can be contained within a single cartridge available in different sizes to accommodate different flow requirements. In single-acting systems, embodiments of a valve constructed in accordance with principles of the present disclosure can be included into the cylinder bottom without the need for a manifold. A multi-functional control valve constructed according to principles of the present disclosure can be used in a variety of applications, including a suspension system and a single or double-acting hitch, for example.

Turning now to the Figures, a hydraulic circuit 100 is shown in FIG. 1. A proportional pressure-reducing/-relieving valve 102 can be used to control a single-acting cylinder 104. By increasing or decreasing the control pressure of the pressure-reducing/-relieving valve 102, a cylinder rod 106 of the single-acting cylinder 104 can be extended or retracted. If the pressure setting of the proportional valve 102 is held constant, the cylinder rod 106 position stays fixed. A variable displacement pump 107 can be adapted to selectively provide a source of pressurized hydraulic fluid to the cylinder 104 through the pressure-reducing/-relieving valve 102.

In the case of a suspension cylinder, the valve 102, operating alone, is kept permanently energized to hold a position. If the valve 102 were de-energized, the cylinder rod 106 would retract under any load. Constantly energizing the coil 108 of the valve 102 to hold a load requires the use of both electric and hydraulic energy, which may be undesirable and pose a safety concern in that the machine behavior may become unpredictable should power be lost during operation.

To avoid the need to constantly energize the coil 108 of the valve 102, the circuit 100 of FIG. 1 includes a solenoid-operated, two-way/two-position poppet valve 115. The function of the solenoid poppet valve 115 in the circuit 100 of FIG. 1 is to work as a load-hold, or position-hold, valve. The position of the cylinder rod 106 can be changed with the pressure-reducing/-relieving valve 102 with the solenoid poppet valve 115 being operated at the same time. As soon as the reference position is reached, the solenoid poppet

valve 115 and the pressure-reducing/-relieving valve 102 can be de-energized. The position of the cylinder rod 106 can be maintained, substantially leakage free, by the solenoid poppet valve 115. An accumulator 120 can be provided to reduce the rate of pressure increase as the cylinder rod 106 strokes. A relief valve 125 can be provided to protect the cylinder 104 and the accumulator 120 from excessive pressure spikes.

The circuit 100 of FIG. 1 uses two solenoids 102, 115 to control the single-acting cylinder 104. The circuit 100 of FIG. 1, however, can allow for the lowering and lifting speed to be adjusted, depending on the control current to the proportional pressure-reducing/-relieving valve 102. If this concept is used with a double-acting system, the pressure in a cylinder rod side 127 of the cylinder 104 can be controlled with the pressure reducing valve 102 without the need of a pressure transducer.

Referring to FIG. 2 an embodiment of a hydraulic circuit 200 constructed in accordance with principles of the present disclosure is shown. The hydraulic circuit 200 is adapted for a single-acting suspension system. In the hydraulic circuit 200 of FIG. 2, the solenoid-operated two way/two position poppet valve 115 of the hydraulic circuit 100 of FIG. 1 is omitted. The hydraulic circuit 200 includes a piloted logic element 215 in operative cooperation with a pressure-reducing/-relieving valve 202. The hydraulic circuit 200 of FIG. 2 also includes a suspension cylinder, a controller or electronic control unit (ECU) 210, a variable displacement pump 220, a tank 221, a load-sense check valve 231, an orifice 240, an accumulator 250, a pressure relief valve 255, a pressure sensor 260, and a position sensor 270.

The variable displacement pump 220 is adapted to provide a source of pressurized fluid, and the tank 221 is adapted to hold a reservoir of fluid. The tank 221 is in fluid communication with the pump 220 such that the pump 220 can selectively draw fluid from the tank 221 for providing the source of pressurized fluid. The pump 220 and the tank 221 are both in selective fluid communication with the control valve 202. A load sense line 230 extends between the pump 220 and the piloted logic element 215. The tank 221 is in selective fluid communication with the pressure relief valve 255.

The suspension cylinder 204 is in selective fluid communication with the pump 220 and the tank 221. The control valve 202, the piloted logic element 215, and the orifice 240 are interposed between the pump 220 and the suspension cylinder 204. The control valve 202 and the piloted logic element 215 are adapted to selectively fluidly connect the suspension cylinder 204 to the pump 220 and the tank 221.

The suspension cylinder 204 includes a reciprocally movable cylinder rod 206 and defines a chamber 208 therein adapted to receive pressurized fluid.

The pressure sensor 260 can be configured to sense the pressure in the chamber 208 (piston-side) of the cylinder 204. The position sensor 270 can be operably arranged with the cylinder rod 206 and adapted to detect the position of the cylinder rod 206 over its stroke between a retracted position and an extended position.

The proportional pressure-reducing/-relief control valve 202 is in electrical communication with the controller 210 and in selective fluid communication with the pump 220 and the tank 221. The control valve 202 includes a spool 212 reciprocally movable over a range of travel between at least a pump flow position in which the pump 220 and a control port 211 of the control valve 202 are in fluid communication with each other and a tank flow position in which the tank 221 and the control port 211 of the control valve 202 are in

fluid communication with each other. The control valve **202** is adapted such that the spool **212** moves in response to a control signal sent to a coil assembly **214** of the control valve **202** received from the controller **210**. The control valve **202** can include a coil **214** which is adapted to selectively move the spool **212**. In embodiments, the control valve **202** can be biased to the pump flow position.

The piloted logic element **215** can be adapted to selectively maintain the cylinder rod in its position when the control valve **202** is de-energized. The piloted logic element **215** is in fluid communication with and interposed between the control valve **202** and the suspension cylinder **204**. The logic element **215** includes a poppet **217** selectively movable between a through-flow position in which fluid can flow in either direction between the chamber **208** of the suspension cylinder **204** and the control port **211** of the control valve **202** and a blocked position in which fluid is prevented from flowing out of the chamber **208** of the suspension cylinder **204** to the control port **211** of the control valve **202**. In embodiments, the logic element **215** is constructed such that fluid can flow from the control port **211** of the control valve to the chamber **208** of the suspension cylinder when the poppet **217** is in the blocked position. The illustrated logic element **215** is biased to the blocked position. The logic element **215** includes a pilot port **216** and is adapted to move from the blocking position to the through-flow position when a pressure at the pilot port **216** exceeds a predetermined value, referred to as a “crack” pressure. The pilot port **216** is in fluid communication with the control port **211** of the control valve **202**.

The load sense line **230** is adapted to provide a load sense signal to the pump **220**. The pump **220** is adapted to vary a flow of pressurized fluid in response to the load sense signal to generate a desired flow to the control valve **202**. The load sense line **230** is in fluid communication with the control port **211** of the pressure-reducing/-relieving control valve **202**, the piloted logic element **215**, and the pump **220** through a load sense port **235**. The load sense line **230** includes the load-sense check valve **231**, which is adapted to prevent a flow of fluid from the pump **220** to the control valve **202** or the logic element **215** but to allow a flow of fluid from a pilot junction **232** along the load sense line **230** to the pump **220**.

In embodiments, the orifice **240** can be disposed between the logic element **215** and the chamber **208** of the suspension cylinder **204**. The orifice **240** can be adapted to control a rate of flow of pressurized fluid to and from the chamber **208** of the suspension cylinder **204** to allow additional tuning of the speed at which the cylinder rod **206** reciprocally extends and retracts.

The accumulator **250** can be placed in fluid communication with and interposed between the piloted logic element **215** and the suspension cylinder **204**. In embodiments, the accumulator **250** can be configured to reduce the rate of pressure increase as the cylinder rod **206** reciprocally strokes.

The relief valve **255** can be provided to protect the suspension accumulator **250** in fluid communication with the suspension cylinder **204** and the suspension cylinder **204** itself against high pressure peaks. The relief valve **255** is in fluid communication with the tank **221** and in parallel fluid relationship with the suspension, cylinder **204**, the accumulator **250**, and the piloted logic element **215**. The relief valve **255** can be adapted such that a pressurized fluid exceeding a predetermined threshold is diverted away from the accumulator **250** and the suspension cylinder **204** to the tank **221**.

The ECU **210** can be provided to operate the circuit **200**. In embodiments, the ECU **210** can comprise any suitable controller known to those skilled in the art. The controller **210** can be in electrical communication with one or more sensors, such as the pressure sensor **260** and/or the position sensor **270** to obtain operational information regarding the condition of the circuit **200** to help the controller **210** operate. The ECU **210** can be used to selectively provide current to the coil assembly **214** of the control valve **202** based on computer-readable operational logic stored on a non-transitory computer readable medium accessed by the processor of the controller **210**.

In embodiments, the control valve **202** can be used to control the single-acting suspension cylinder **204**. By increasing or decreasing the control pressure of the control valve **202**, the cylinder rod **206** can be extended or retracted. If the pressure setting of the control valve **202** is held constant, the cylinder rod **206** can remain fixed in place.

In embodiments, a hydraulic manifold can be used to control the position of the suspension cylinder **204**. When the load on the cylinder **204** changes, the position will change and then the suspension stroke in one direction will be decreased. Therefore, the ECU **210** can be adapted to control the cylinder **204** back to its nominal position such that it has the maximum suspension stroke available. As soon as the control valve **202** is operated (e.g., control current to the coil **214** is higher than the offset), the valve **202** is controlling a pressure at the pilot port **216** of the logic element **215**. The logic element **215** opens in response to the pilot pressure, thereby allowing flow to or from the cylinder **204**. Furthermore, a load sense signal is sent through the load-sense check valve **230** to the load-sense port **235** of the pump **220** which is adapted to generate the required pressure/flow.

If the pressure controlled with the pressure-reducing/-relieving control valve **202** is lower than the pressure in the chamber **208** of the cylinder **204** but higher than the crack pressure of the logic element **215**, the logic element **215** is in the through-flow position and fluid in the chamber **208** of the suspension cylinder **204** drains therefrom, thereby retracting the cylinder rod **206** of the cylinder **204**. If the pressure controlled with the pressure-reducing-relieving valve **202** is higher than the pressure in the cylinder **204** and the crack pressure of the logic element **215**, the logic element **215** is in the through-flow position and fluid flows from the pump **220** to the chamber **208** of the suspension cylinder **204**, thereby extending the cylinder rod **206** of the cylinder **204**.

As soon as the reference position is reached, the control current for the coil **214** of the control valve **202** can be set to zero, and the logic element **215** closes in response to the pilot pressure dropping below the crack pressure of the logic element **215** such that the poppet **217** moves to the blocked position. With the logic element **215** closed, the position of the cylinder rod **206** of the cylinder **204** is maintained until the load changes.

In one configuration, when the digital controller output of the controller **210** is switched off, no current is applied to the pressure-reducing/-relieving control valve **202**, and the controlled pressure is lower than the crack pressure setting of the logic element **215**. The logic element **215** is closed, and there is no load sense signal through the load-sense check valve **230** in the load sense line **231** in communication with the pump **220**.

An operative condition referred to as “on-high” is shown in FIG. 3. When the output of the digital controller **210** is switched to an operative condition referred to as “on-high,”

the maximum current is applied to the solenoid assembly 214 of the pressure-reducing/-relieving control valve 202, resulting in the maximum pressure setting of the control valve 202 at the control port. A fluid region upstream of the logic element 215 relative to the suspension cylinder 204 (in the illustrated embodiment, the pilot port 216) is in fluid communication with the control port 211 of the control valve 202, and the poppet 217 of the logic element 215 moves to the through-flow position when the pressure at the fluid region upstream of the logic element 215 exceeds a predetermined crack pressure.

The load sense signal sensed at the control port 211 of the pressure-reducing/-relieving control valve 202 causes the pump 220 to increase the supply pressure to the pressure-reducing/-relieving control valve 202 to meet the pressure requirements of the load. As fluid flows from the control port 211 of the pressure-reducing/-relieving control valve 202 and through the logic element 215, the cylinder rod 206 will extend. In embodiments, the position sensor 270 can be used to detect the position of the cylinder rod 206, and/or the pressure sensor 260 can be used to detect the pressure in the piston-side of the suspension cylinder 204 (the chamber 208). The position signal and/or the pressure signal generated by the respective sensor 270, 260 can be sent to the ECU 210 which is adapted to use the signal(s) to control the operation of the control valve 202 and/or the pump 220.

When the reference position or pressure is reached, the digital controller output of the ECU 210 is switched off again. This causes the pressure at the control port 211 of the proportional pressure-reducing/-relieving control valve 202 to drop below the crack pressure of the logic element 215. The logic element 215 closes (the poppet 217 moves back to the blocking position) and holds the pressure in the piston-side of the cylinder 204.

To retract the position of the cylinder rod 206 or to reduce the pressure in the piston-side of the cylinder 204, the digital controller output of the ECU 210 can be switched to a condition called "On-low," as shown in FIG. 4. The graph in FIG. 4 illustrates the controller output switching between on and off states in a defined cycle time. Due to the inductance of the coil circuit, the current which is applied to the control valve 202 oscillates at about 30% percent of the maximum current, which would have been reached if the output is permanently switched on (see FIG. 3).

The ECU 210 can be adjusted to selectively turn the digital controller output on and off for a predetermined cycle time. For example, in one arrangement, the ECU 210 can vary the cycle time such that the output can be alternately switched on for x cycles, then switched off for 2x cycles, then switched on for x cycles, switched off for 2x cycles and so on, thereby creating a pseudo pulse-width modulation (PWM) control current. In some embodiments, x can be equal to about 1, but other time ratios can be used in other embodiments.

The current applied to the coil 214 of the pressure-reducing/-relieving control valve 202 to retract the cylinder rod 206 of the cylinder 204 or lower the piston-side pressure of the cylinder 204 is shown in FIG. 4. With a low current applied to the pressure-reducing/-relieving valve 202, the pressure sensed by the logic element 215 is slightly higher than the crack pressure which is required to open the logic element 215. The logic element 215 will open. Since the pressure in the piston-side of the cylinder 204 is higher than the pressure controlled with the pressure-reducing/-relieving control valve 202, the hydraulic oil will flow from the cylinder 204 through the orifice 240, through the logic element 215, and through the pressure-reducing/-relieving

control valve 202 in relieving mode to the tank 221. This flow of hydraulic oil from the cylinder 204 to the tank 221 will continue as long as the controller output is in this described "On-low" state or until the pressure in the cylinder 204 reaches the pressure setting of the proportional pressure-reducing/-relieving control valve 202.

Referring to FIG. 5, an example of the control pressure, cylinder pressure, and proportional pressure-reducing/-relieving control valve current over time for a single-acting system similar to the circuit 200 of FIG. 2 is shown. P1 is the control pressure between the proportional pressure-reducing/-relieving control valve 202 and the logic element 215. P4 is the pressure of the cylinder 204. I is the current to the coil 214 of the proportional pressure-reducing/-relieving control valve 202.

Referring to FIG. 6, another embodiment of a hydraulic circuit 300 for a single-acting system constructed in accordance with principles of the present disclosure is shown. The hydraulic circuit 300 includes a pressure-reducing/-relieving control valve 302, a suspension cylinder 304, a controller 310, a piloted logic element 315, a constant flow pump 320, a tank 321, an orifice 340, an accumulator 350, a pressure relief valve 355, a pressure sensor 360, and a position sensor 370.

The piloted logic element 315 is in operative cooperation with the pressure-reducing/-relieving valve 302. The proportional pressure-reducing/-relief control valve 302 is in electrical communication with the controller 310 and in selective fluid communication with the pump 320. The logic element 315 is in fluid communication with and interposed between the control valve 302 and the suspension cylinder 304. These components can operate as explained above to control the cylinder 304.

The constant flow pump 320 is adapted to provide a constant flow of pressurized fluid. In thus case, the circuit 300 does not include the load sense function or the hydraulic load sense line 230 including the check valve 231 as is shown in the hydraulic circuit 200 of FIG. 2. To improve hydraulic efficiency, the circuit 300 of FIG. 6 can include a solenoid relief valve 305 or an unloading pressure compensator interposed between the constant flow pump 320 and the control valve 302. The solenoid relief valve 305 can be in electrical communication with the controller 310 such that the ECU 310 can be used to control its operation. The construction and functionality of the hydraulic circuit 300 of FIG. 6 can be similar in other respects to the hydraulic circuit 200 of FIG. 2.

Referring to FIG. 7, another embodiment of a hydraulic circuit 400 for a single-acting system constructed in accordance with principles of the present disclosure is shown. The hydraulic circuit 400 includes a pressure-reducing/-relieving valve 402, a suspension cylinder 404, a controller 410, a piloted logic element 415, a variable displacement pump 420 with a load sense line 430, a tank 421, an accumulator 450, a pressure relief valve 455, a pressure sensor 460, and a position sensor 470.

The piloted logic element 415 is in operative cooperation with the pressure-reducing/-relieving valve 402. The proportional pressure-reducing/-relief control valve 402 is in electrical communication with the controller 410 and in selective fluid communication with the pump 420. The logic element 415 is in fluid communication with and interposed between the control valve 402 and the suspension cylinder 404. These components can operate as explained above to control the cylinder 404.

The circuit 400 of FIG. 7 includes a one-way restrictor 441 rather than an orifice 240 as found in the hydraulic

circuit 200 of FIG. 2. The one-way restrictor 441 is disposed between the logic element 415 and the chamber 408 of the suspension cylinder 404. In embodiments, the one-way restrictor 441 is adapted to control a rate of flow of pressurized fluid in one direction between the piloted logic element 415 and the cylinder 404, either to or from the chamber 408 of the suspension cylinder 404.

In the illustrated embodiment, the one-way restrictor 441 does not restrict the flow of fluid from the piloted logic element 415 to the cylinder 404, but restricts the flow of fluid from the cylinder 404 to the piloted logic element 415. By using the one-way restrictor 441 as shown, the cylinder rod 406 of the suspension cylinder 404 can be extended very quickly while providing a slow controlled retraction (alternatively, the cylinder rod 406 could be retracted very quickly while providing slow, controlled extension using a one-way restrictor arranged in the opposite fashion). This can be beneficial in special situations involving front-axle suspension systems. The construction and function of the hydraulic circuit 400 of FIG. 7 can be similar in other respects to the hydraulic circuit 200 of FIG. 2.

Referring to FIG. 8, an embodiment of a hydraulic circuit 500 constructed in accordance with principles of the present disclosure for a double-acting suspension system is shown. The hydraulic circuit 500 of FIG. 8 includes a piston-side pressure-reducing/-relieving control valve 502, a rod-side pressure-reducing/-relieving control valve 503, a suspension cylinder 504, a controller 510, a pair of piloted logic elements 515, 516, a variable displacement pump 520 with a load sense line 530, a tank 521, a piston-side orifice 540, a rod-side orifice 541, a piston-side accumulator 550, a rod-side accumulator 551, a pressure relief valve 555, a piston-side pressure sensor 560, a rod-side pressure sensor 561, and a position sensor 570.

The double-acting suspension system 500 uses a piston side 526 and a rod side 527 of a chamber 508 of the suspension cylinder 504 for the suspension function. The suspension cylinder 504 includes a body 505 and a piston assembly 507 disposed within the body 505 that is reciprocally movable over a range of travel between a retracted position and an extended position. The piston assembly 507 includes a piston 509 and a rod 506, at least a portion of which extends from the body 505. The body 505 defines the piston-side chamber 526 and the rod-side chamber 527.

The load sense pump 520 can be adapted to provide a source of pressurized hydraulic fluid to both the piston-side pressure-reducing/-relieving control valve 502 and the rod-side pressure-reducing/-relieving control valve 503, which are all in electrical communication with the ECU 510. The control valves 502, 503 are each in turn associated with the piloted logic elements 515, 516, the orifices 540, 541, and the accumulators 550, 551, respectively.

The load sense line 530 fluidly connects the control port 511 of the piston-side pressure-reducing/-relieving control valve 502 and its associated piloted logic element 515 with the pump 520 through a resolver 531. The load sense line 530 also fluidly connects the control port 511 of the rod-side pressure-reducing/-relieving control valve 503 and its associated piloted logic element 516 with the pump 520 through the resolver 531. The load sense line 530 is adapted to provide a load sense signal to the pump 520 through a load sense port 535. The pump 520 is adapted to vary a flow of pressurized fluid in response to the load sense signal to generate a desired flow to the control valve 202.

The pair of orifices 540, 541 is respectively disposed between the piston-side logic element 515 and the cylinder 504 and between the rod-side logic element 516 and the

cylinder 504. Both sides 526, 527 of the cylinder chamber 508 are independently connected to the respective accumulators 550, 551. The position control of the cylinder rod 506 can be performed by increasing or decreasing the oil volume in the piston side 526 of the cylinder 504. The rod side 527 of the cylinder 504 can be pressurized with a constant or variable pressure. The illustrated circuit 500 of FIG. 8 provides a variable rod side pressure with the disclosed circuit concept.

The function of the circuit 500 of FIG. 8 is similar to the single acting suspension circuit 200 of FIG. 2. The position control (cylinder piston side 526) works in a manner similar to that described above in connection with a single-acting system, such as in FIG. 2. For the pressure control in the cylinder rod side 527, several scenarios are possible. The pressure in the cylinder rod side 527 can be controlled by using the rod-side pressure sensor 561 to detect the pressure in the rod side 527 of the cylinder 504. The rod-side proportional pressure-reducing/-relieving control valve 503 can be operated using a closed control loop with a feedback or feed-forward control loop such as a PID-controller or equivalent algorithm to control the pressure to the reference value. The pressure in the cylinder rod side 527 can be increased and decreased in a similar manner as the position of the cylinder rod 506 is controlled. If the pressure controlled with the rod-side proportional pressure-reducing/-relieving control valve 503 is lower than the pressure in the rod side 527 of the cylinder 504 but higher than the crack pressure of the rod-side logic element 516, the pressure in the rod side 527 of the cylinder 504 will be reduced. If the pressure controlled with the rod-side proportional pressure-reducing/-relieving control valve 503 is higher than the pressure in the rod-side 527 of the cylinder 504, the pressure in the rod side 527 of the cylinder 504 will be increased.

A second option to control the pressure in the cylinder rod side 527 is to set the current to the rod-side proportional pressure-reducing/-relieving control valve 503 to regulate a desired pressure according to the characteristic curve of the control valve 503 during cylinder piston side 526 adjustments. One way this can be accomplished is by using the ECU 510 with a PWM-output with current feedback to control the current to the rod-side proportional pressure-reducing/-relieving control valve 503.

A third option (also used for position control) to control the pressure in the cylinder rod side 527 is to use the rod-side proportional pressure-reducing/-relieving control valve 503 controlled by a digital output from the controller 510 to provide no output, "on-low", or "on-high" current to the control valve as previously described above. A double-acting system can be configured to replicate this control scheme to control the piston-side pressure-reducing/-relieving control valve 502 and the rod-side proportional pressure-reducing/-relieving control valve 503. This method is beneficial, since all ECU's may not have free PWM outputs available. The rod-side pressure sensor 561 can be used to detect if the pressure in the rod-side 527 of the cylinder 504 should decrease, increase, or if it is in the acceptable range. The pressure is then adjusted using either an "on-low" current or "on-high" current or maintained with no current to the valve. The discussion of the operation of the circuit 200 of FIG. 2 is referred to for further details, which are applicable to the operation of the rod-side 527 of the circuit 500 of FIG. 8, as well. In a double-acting system, the rod and piston side 527, 526 of the cylinder 504 can be controlled independently and concurrently.

Referring to FIG. 9, another embodiment of a hydraulic circuit 600 constructed in accordance with principles of the

present disclosure is shown, which is a double-acting system similar to the circuit 500 of FIG. 8. The hydraulic circuit 600 of FIG. 9 includes a piston-side pressure-reducing/-relieving control valve 602, a rod-side pressure-reducing/-relieving control valve 603, a suspension cylinder 604, a controller 610, a piston-side piloted logic elements 615, a piston-side piloted logic element 616, a variable displacement pump 620 with a load sense line 630, a tank 621, a piston-side accumulator 650, a rod-side accumulator 651, a pressure relief valve 655, a piston-side pressure sensor 560, a rod-side pressure sensor 561, and a position sensor 570.

The circuit 600 of FIG. 9 is the same as the circuit 500 of FIG. 8 except that the piston-side orifice 540 and the rod-side orifice 541 of the circuit 500 of FIG. 8 are replaced with a pair of one-way restrictor valves 642, 643, respectively. The orifice elements of the one-way restrictor valves 642, 643 can have a different size from each other in some embodiments.

Referring to FIG. 10, another embodiment of a hydraulic circuit 700 constructed in accordance with principles of the present disclosure is shown, which is similar to the circuit 500 of FIG. 8. The hydraulic circuit 700 comprises a double-acting suspension system which uses a piston side 726 and a rod side 727 of the chamber 708 of a suspension cylinder 704 for the suspension function. The hydraulic circuit 700 of FIG. 10 includes a piston-side multifunctional cartridge control valve 705, a rod-side multifunctional cartridge control valve 706, the suspension cylinder 704, a controller 710, a variable displacement pump 720 with a load sense line 730, a tank 721, a piston-side orifice 740, a rod-side orifice 741, a piston-side accumulator 750, a rod-side accumulator 751, a piston-side pressure sensor 760, and a rod-side pressure sensor 761.

To obtain a space-saving option, the pair of multifunctional cartridge control valves 705, 706 can be provided, which each integrate a proportional pressure-reducing/-relieving control valve 702, a piloted logic element 715, and a check valve 712 that perform the same function as the corresponding components of the circuit 500 of FIG. 8. For example, the integrated components of the piston-side multifunctional cartridge control valve 705 correspond to the piston-side pressure-reducing/-relieving valve 502, the piston-side logic element 515, and the portion of the resolver 531 in the load sense line 530 configured to provide a load sense signal for the piston-side of the cylinder 504. In embodiments, the orifices 740, 741 can be integrated into each of the multifunctional cartridge control valves 705, 706, respectively.

The variable displacement pump 720 is adapted to provide a source of pressurized fluid, and the tank 721 is adapted to hold a reservoir of fluid. The tank 721 is in fluid communication with the pump 720. The load sense pump 720 can be adapted to provide a source of pressurized hydraulic fluid to both a piston-side multifunctional cartridge control valves 705 and a rod-side multifunctional cartridge control valves 706, which are all in electrical communication with an ECU 710.

The suspension cylinder 704 is in selective fluid communication with the pump 720 via the piston-side multifunctional cartridge control valve 705 and the rod-side multifunctional cartridge control valve 706. The suspension cylinder 704 defines a chamber 708 therein adapted to receive pressurized fluid. The piston-side 726 and the rod-side 727 of the cylinder chamber 708 are independently connected to the piston-side and rod-side accumulators 750, 751 and pressure sensors 760, 761, respectively. The pres-

sure sensors 760, 761 can be disposed between the orifices 740, 741, respectively, and the cylinder 704.

In the circuit 700 of FIG. 10, a load sense check valve 780 can be placed in a common branch 782 of the load sense line 730. The load sense check valve 780 can help to completely unload the load sense pump 720 below the residual pressure of the pressure reducing portion of the multifunctional cartridge control valves 705, 706.

Referring to FIG. 11, an embodiment of a multi-functional cartridge valve 800 constructed in accordance with principles of the present disclosure is shown. The illustrated valve 800 includes a control valve portion, a logic element portion, and a load sense portion contained within a single cartridge arrangement. In embodiments, the cartridge valve 800 can be housed within a suitably configured valve body.

In the illustrated valve 800, an electro-magnetic actuator assembly in the form of a solenoid assembly 850 includes a coil 855, a tube 819, a movable plunger or armature 831, and a pole piece 843. The solenoid 850 has a proportional characteristic of magnetic (attractive) force between the pole piece 843 and the plunger 831 which is proportional to the current applied to the coil 855. The tube 819 can comprise a bi-metallic assembly consisting of magnetically attractive and non-attractive materials. The geometry of the magnetically attractive and non-attractive materials can be configured to determine the magnetic force characteristic of the solenoid 850. A non-magnetic washer 828 between the pole piece 843 and the plunger 831 prevents the plunger 831 from latching to the pole piece 843 via residual magnetism.

A pilot spring 829 transmits the solenoid force to a pilot poppet 827. The equilibrium position of the plunger 831 at a given coil current is determined when the magnetic force balances with the force of the pilot spring 829. An adjusting screw 830 sets the position of the plunger 831 with no current applied to the coil. Turning the adjusting screw 830 in and out of the plunger 831 allows the user to set the desired pressure setting of the valve at a give current.

A threaded plug 832 at the top of the tube 819 can be removed to allow adjustment of the adjusting screw 830 to provide a pressure setting with no current applied to the coil 855. A spring ring 833 can be provided to retain the plug 832 after the valve 800 is set to the desired pressure setting and helps prevents unintended removal of the plug 832. A proximal outer area between the plug 832 and the tube 819 may also be filled with epoxy for further tamper-proof protection, in which case the threaded plug 832 can be adjusted by the manufacturer and then encased with an epoxy. An O-ring 841 and a back-up ring 842 can provided to form a seal between the tube 819 and the plug 832 to help prevent external leakage. A distal portion 860 of the tube 819 includes a threaded external surface 862 adapted to threadingly engage the cavity of a valve body (not shown).

The valve 800 defines five fluid connection ports (Ports A-E) which correspond to those shown for the multifunctional cartridge control valves 705, 706 of the hydraulic circuit 700 of FIG. 10. Port A is disposed along a longitudinal axis of the valve 800 on the distal face end 880 of a logic element cage 814. Ports B-E are located along the outer periphery of the valve housing with fluid connections in the radial direction. The Ports E, D, C, B, A are separated from adjacent Ports by an O-ring 837, 834, 812, 811 and an associated pair of back-up rings 836, 835, 805, 804, respectively, to prevent fluid from leaking from one port to another. In other embodiments, the Ports E, D, C, B, A may be separated by a single molded seal.

The logic element cage 814 defines Ports A and B. A logic element seat 818 defines Port C. A pressure-reducing/-

relieving control valve cage **820** defines Ports E and D. An O-ring **840** prevents external leakage proximally from Port E.

A control valve portion can include the control valve cage **820** and a hollow spool **821**. The control valve cage **820** defines a longitudinal interior passageway **910**, a tank port E, and a pump port D. The tank and pump ports E, D are in communication with the interior passageway **910** of the control valve cage **820**. The spool **821** defines a longitudinal spool passageway **912** and a plurality of cross holes **914** radially arranged about the spool **821**. The cross holes **914** of the spool **821** are in communication with the spool passageway **912** and the interior passageway **910** of the control valve cage **820**. The spool **821** is disposed within the interior passageway **910** of the control valve cage **820** and reciprocally movable over a range of travel between a pump flow position in which the pump port D of the control valve cage **820** is open and the tank port E of the control valve cage **820** is closed and a tank flow position in which the tank port E of the control valve cage **820** is open and the pump port D of the control valve cage **820** is closed. The spool **821** is biased to the pump flow position.

The control valve cage **820** has a “floating” connection with the tube **819** through an oval spring ring **824** that retains the valve cage **820** to the tube **819** when the valve **800** is removed from the cavity of a valve body. The spring ring **824** is trapped in a machined groove **864** provided on the outer diameter of the cage **820** and a corresponding groove **866** on the inner diameter of the tube **819**. When the valve **800** is installed in the cavity of a valve body, the “floating” portion of the valve **800** is trapped between the distal face end **870** of the tube **819** and a shoulder **872** of the control valve cage **820** at a proximal outer end of the cavity of the valve body and a distal bottom of the cavity and a distal face end **880** of the logic element cage **814** at the distal bottom of the cavity.

The reciprocally-movable spool **821** is disposed within the control valve cage **820** and is adapted to selectively open and close the flow area at Port D and Port E. A filter core **822** is installed in the spool **821**. The filter core **822** is interposed between the radial cross holes **914** of the spool **821** and the orifice **825** of the pilot poppet assembly. The filter core **822** incorporates an orifice hole and restricts the size of particle that can pass between the filter core **822** and the spool **821** before reaching the orifice hole. In embodiments, the filter core **822** can be retained within the spool **821** by a swaging operation that flares an upper lip of the filter core **822** after it is inserted into the spool **821**.

A spool bias spring **844** can be provided that is adapted to bias the spool **821** to a position in which the spool **821** occludes Port E. A distal end **882** of the spool bias spring **844** is installed in a blind hole **884** at a proximal end **885** of the spool **821** to urge the spool **821** in a distal direction along the longitudinal axis to a position that closes off Port E (as shown) when the pressure proximally above and distally below the spool **821** is balanced. A spring ring **823**, which is installed in a groove at the proximal end **885** of the spool **821**, provides a positive stop in the distal direction for the spool **821** when it contacts an angled surface **887** defined between a proximal bore **888** of the cage **820** having a first diameter and a distal bore **889** of the control valve cage **820** having a second diameter which is smaller than the diameter of the proximal bore **888**. An O-ring **838** and an associated back-up ring **839** help seal the spool bias spring chamber **893** from Port E.

In embodiments, the electro-magnetic actuator has a pilot poppet assembly that includes the pilot poppet **827**, the pilot

spring **829** interposed between the armature **831** and the pilot poppet **827**, a seat **826** retained within the pole piece **843** and defining a longitudinal bore **930** therethrough, and an orifice **825** interposed between the longitudinal bore **930** and the spool bias spring **844**. The orifice **825** is in communication with the spool passageway **912**. The pilot spring **829** urges the pilot poppet **827** into sealing engagement with the seat **826** such that the longitudinal bore **930** is occluded until a poppet lifting force is applied in a direction from the orifice toward the pilot spring **829**.

A proximal end **891** of the spool bias spring **844** rests against the orifice disc **825** located within the pole piece **843**. The orifice disc **825** is engaged with the hardened seat **826**. The seat **826** is secured via an interference fit between the seat **826** and the pole piece **843**. The seat **826** is further retained from moving proximally by an angled surface, created by the change in diameter, at the proximal end of the seat **826**, which makes positive contact with a slight change in diameter of a bore of the pole piece **843**. The pilot poppet **827** is engaged with the seat **826** to define a low leakage seal until sufficient pressure is present distally below the seat **826** to lift the pilot poppet **827** off the seat **826** in a proximal direction against the spring force created by the solenoid actuator **850** above.

In embodiments, the valve **800** can include a load sense portion in communication with both the control valve portion and a logic element portion. The illustrated load sense portion includes the logic element seat **818** and a load sense check ball **806**.

The logic element seat **818** is interposed between the control valve cage **820** and a logic element cage **814**. The logic element seat **818** defines a longitudinal load sense passageway **920** therethrough and a load sense port C, which is in communication with the load sense passageway **920**. The load sense passageway **920** is in communication with the spool passageway **912** of the control valve portion and a logic element poppet **817**.

The logic element seat **818** has an interference fit with the pressure reducing/relieving control valve cage **820**, which is proximally above the logic element seat **818**, and the logic element cage **814**, which is distally below the logic element seat **818**. In other embodiments, the logic element seat **818** can be connected to the two cages **814**, **820** via a threaded connection or other mechanical device such as a spring pin or spring ring (not shown).

The logic element seat **818** defines Port C which comprises a load sense port adapted to actuate a load sense pump or other pump control device, and incorporates a reverse-flow check ball **806**. The check ball **806** sits against a seat **892** in the radial passage defined in the logic element seat **818** and blocks the flow of hydraulic fluid when the pressure at Port C is higher than the internal valve pressure between the spool **821** and a logic element poppet **817**. A spring ring **808**, which is installed in a machined groove **895** in the seat **818**, holds the check ball **806** in place. A roll pin **802** is inserted into a blind hole **896** in the seat **818** about one hundred eighty degrees away from the check ball seat to fix the rotational position of the spring ring **808**.

In embodiments, the valve **800** includes a logic element portion which is in communication with the control valve portion. The illustrated logic element portion includes the logic element cage **814** and the logic element poppet **817**. The logic element cage **814** defines a longitudinal interior logic element passageway **925** and a logic element port B, which is in communication with the logic element passageway **925**. The logic element passageway **925** is in communication with the spool passageway **912**.

The logic element poppet **817** is disposed within the logic element passageway **925** of the logic element cage **814** and reciprocally movable over a range of travel between a blocking position in which the logic element port B of the logic element cage **814** is closed and a logic element through-flow position in which the logic element port B of the logic element cage **814** is open. The logic element poppet **817** is biased to the blocking position such that the logic element poppet **817** remains in the blocking position until a pressure at least equal to a crack pressure is applied to the logic element poppet **817** against the biasing force, thereby unseating the logic element poppet **817** from the blocking position and moving the logic element poppet **817** toward the through-flow position.

The logic element poppet **817** is engaged with the logic element seat **818** via the force of a logic element spring **816**. When the pressure between the control valve spool **821** and the logic element poppet **817** causes the force that acts to open the logic element poppet **817** to exceed the force of the logic element spring **816** that acts to close the logic element poppet **817**, the logic element poppet **817** lifts off the logic element seat **818**, thereby allowing flow to Port B defined by the logic element cage **814**. The diameter of the logic element seat **818** matches the bore diameter of the poppet **817** so that pressure at Port B will not act to open the logic element poppet **817**.

The second port A can be in fluid isolation with respect to the logic element port B of the logic element cage **814**. In the illustrated embodiment, Port B is internally sealed off from Port A by an O-ring **810** and a piston seal **801** on an external surface of the logic element poppet **817**. The piston seal **801** provides a running seal between the logic element poppet **817** and the logic element passageway **925** of the logic element cage **814**.

A washer **813** mounted to the logic element poppet **817** provides a seat for a proximal end of the logic element spring **816** which provides a bias force on the logic element poppet **817**. A spring guide **815** supports the opposing distal end of the spring **816**, provides guidance for the logic element spring **816**, and hydraulic fluid communication of the logic element spring chamber **898** to Port A. The spring guide **815** defines a passageway **940** therethrough. In the illustrated embodiment, the passageway **940** of the spring guide has a longitudinal segment and a plurality of radial segments in communication with the longitudinal segment. The passageway **940** of the spring guide **815** is in communication with the logic element passageway **925** and the second port A of the logic element cage **814**. The illustrated spring guide **815** is retained by a spring ring **807**. The spring ring **807** is installed in a machined groove **899** in the logic element cage **814**. In embodiments, Port A is connected to tank, or in yet other embodiments can be connected to a pilot signal if the application required the logic element pressure setting to be variable.

In embodiments of using a multi-functional cartridge valve constructed according to principles of the present disclosure, hydraulic fluid can be supplied from a pump to Port D of the valve **800**. The control valve spool **821** allows flow from Port D to the internal volume distally below the spool **821**. Fluid under the spool **821** communicates with the internal volume above the spool **821** (the spool bias spring chamber **893**) through the filter core **822**. Fluid above the spool **821** communicates with the internal volume below the pilot poppet **827** through the orifice disc **825**. The pressure exerted by the fluid in the internal volume below the pilot poppet **827** acts to push the pilot poppet **827** up off the seat **826**. When the pressure force acting on the pilot poppet **827**

exceeds the force exerted by the pilot spring **829** on the pilot poppet **827**, the pilot poppet **827** unseats and fluid passes between the seat **826** and the pilot poppet **827**, through the communication passage between the pole piece **843** and the tube **819**, and out a cylindrical hole provided in the tube thread to Port E.

Flow through the area created when the pilot poppet **827** lifts off the seat **826** results in a pressure drop in the volume just distally under the pilot poppet **827**. The difference in pressure between the volume under the seat **826**, the volume above the control valve spool **821** and distally below the spool **821** causes flow through the filter core **822** and the orifice disc **825**.

The resulting pressure drop across the filter core orifice causes an unbalanced pressure force on the spool **821**. When the net pressure force acting upon the spool **821** exceeds the downward force of the spool bias spring **844**, the spool **821** moves proximally, thereby closing off flow from Port D.

The pressure in the volume distally under the spool **821** also acts to unseat the logic element poppet **817** from the seat **818** in the lower logic element portion of the valve. The logic element poppet **817** is biased against the seat **818** by the force exerted by the logic element spring **816** in the lower portion of the valve. The logic element poppet **817** blocks the passage of flow between the volume distally under the control valve spool **821** and Port B of the valve until the logic element poppet **817** is unseated.

With no current applied to the coil **855**, the pressure in the volume below the spool **821** is less than what is required to unseat the logic element poppet **817**. When current is applied to the coil **855**, the plunger **831** is attracted to the pole piece **843**. This compresses the pilot spring **829** and increases the force holding the pilot poppet **827** against the seat **826** resulting in a higher pressure above and below the spool **821** before the spool **821** shifts to close off Port D. When the current is increased enough, the pressure in the volume below the spool **821** exceeds the crack pressure of the logic element poppet **817** and the logic element poppet **817** unseats from the logic element seat **818**, thereby allowing flow either to or from Port B.

If the pressure at Port B is lower than the pressure in the volume under the spool **821**, flow will enter the valve **800** from Port D, travel through the spool **821**, through the flow area created by the logic element seat **818** and the logic element poppet **817**, and out of Port B. If the pressure at Port B is higher than the pressure under the spool **821**, flow will enter the valve **800** from Port B and pass through the area created by the logic element seat **818** and the logic element poppet **817**. This flow will increase the pressure in the volume under the spool **821**, thereby causing the spool **821** to shift up and close off Port D. With a steady current maintained to the coil **855**, the pressure above the spool **821** will remain relatively constant. Additional flow from Port B will cause the spool **821** to continue shifting up until Port E is opened. Flow from the volume under the spool **821** passes through the spool **821** and out Port E. Flow in or out of Port B will continue until the pressure under the spool **821** and at Port B is equalized or until the current at the coil **855** is dropped so that the pressure under the spool **821** is below the crack pressure of the logic element poppet **817**. Once the pressure under the spool **821** is below the crack pressure of the logic element poppet **817**, the logic element poppet **817** will again reseat against the logic element seat **818** and stop flow to or from Port B.

The valve **800** provides a load sense port with a reverse flow check ball **806** from Port C. The load sense check ball **806** is movably arranged with the load sense port C such that

the load sense check ball **806** substantially prevents the flow of fluid into the load sense passageway **920** through the load sense port C but allows the flow of fluid from the load sense passageway **920** out of the load sense port C.

In embodiments, Port A is a drain of the logic element spring chamber **898** to the system reservoir. In yet other embodiments, Port A could receive a pilot signal that would allow the pressure setting of the logic element to be variable.

All references, including publications, patent applications, and patents, cited herein are hereby incorporated by reference to the same extent as if each reference were individually and specifically indicated to be incorporated by reference and were set forth in its entirety herein.

The use of the terms “a” and “an” and “the” and similar referents in the context of describing the invention (especially in the context of the following claims) are to be construed to cover both the singular and the plural, unless otherwise indicated herein or clearly contradicted by context. The terms “comprising,” “having,” “including,” and “containing” are to be construed as open-ended terms (i.e., meaning “including, but not limited to,”) unless otherwise noted. Recitation of ranges of values herein are merely intended to serve as a shorthand method of referring individually to each separate value falling within the range, unless otherwise indicated herein, and each separate value is incorporated into the specification as if it were individually recited herein. All methods described herein can be performed in any suitable order unless otherwise indicated herein or otherwise clearly contradicted by context. The use of any and all examples, or exemplary language (e.g., “such as”) provided herein, is intended merely to better illuminate the invention and does not pose a limitation on the scope of the invention unless otherwise claimed. No language in the specification should be construed as indicating any non-

claimed element as essential to the practice of the invention. Preferred embodiments of this invention are described herein, including the best mode known to the inventors for carrying out the invention. Variations of those preferred embodiments may become apparent to those of ordinary skill in the art upon reading the foregoing description. The inventors expect skilled artisans to employ such variations as appropriate, and the inventors intend for the invention to be practiced otherwise than as specifically described herein. Accordingly, this invention includes all modifications and equivalents of the subject matter recited in the claims appended hereto as permitted by applicable law. Moreover, any combination of the above-described elements in all possible variations thereof is encompassed by the invention unless otherwise indicated herein or otherwise clearly contradicted by context.

What is claimed is:

1. A hydraulic suspension system comprising:

a controller;

a pump adapted to provide a source of pressurized fluid and a tank adapted to hold a reservoir of fluid, the tank in fluid communication with the pump;

a suspension cylinder in selective fluid communication with the pump, the suspension cylinder defining a chamber therein adapted to receive pressurized fluid;

a proportional pressure-reducing/-relief control valve interposed between the pump and the suspension cylinder and between the suspension cylinder and the tank, the control valve in electrical communication with the controller and in selective fluid communication with the pump, the tank, and the suspension cylinder, the control valve including a spool reciprocally movable over a range of travel between at least a pump flow

position in which the pump and a control port of the control valve are in fluid communication with each other and a tank flow position in which the tank and the control port of the control valve are in fluid communication with each other, the control valve adapted such that the spool moves in response to a control signal received from the controller;

a logic element interposed between the control valve and the suspension cylinder, the logic element in fluid communication with the control valve and in selective fluid communication with the suspension cylinder, the logic element including a poppet selectively movable between a through-flow position in which fluid can flow in either direction between the chamber of the suspension cylinder and the control port of the control valve and a blocked position in which fluid is prevented from flowing out of the chamber of the suspension cylinder, the poppet biased to the blocking position, the poppet adapted to move from the blocking position to the through-flow position when a pressure at a fluid region upstream of the poppet exceeds a predetermined crack pressure, the fluid region upstream of the logic element poppet being in fluid communication with the control port of the control valve.

2. The hydraulic suspension system according to claim 1, wherein the logic element comprises a piloted logic element including a pilot port, the poppet of the logic element adapted to move from the blocking position to the through-flow position when a pressure at the pilot port exceeds the predetermined crack pressure, and the pilot port being in fluid communication with the control port of the control valve.

3. The hydraulic suspension system according to claim 2, wherein the pressure-reducing/-relieving control valve and the logic element are adapted such that, if the pressure controlled with the pressure-reducing/-relieving control valve is higher than the crack pressure of the logic element but lower than the pressure in the chamber of the suspension cylinder, the poppet of the logic element is in the through-flow position and fluid in the chamber of the suspension cylinder drains therefrom, and if the pressure controlled with the pressure-reducing/relieving valve is higher than the crack pressure of the logic element and the pressure in chamber of the suspension cylinder, the poppet of the logic element is in the through-flow position and pressurized fluid flows from the pump to the chamber of the suspension cylinder.

4. The hydraulic suspension system according to claim 2, wherein the controller is configured such that, once the controller receives a signal indicating that the suspension cylinder reaches a reference position or a reference pressure, the controller is adapted to control the control valve such that the spool of the control valve is disposed in the tank flow position such that the pressure at the pilot port of the logic element falls below the crack pressure, thereby moving the poppet of the logic element to the blocked position to maintain the suspension cylinder in the reference position or the reference pressure.

5. The hydraulic suspension system according to claim 2, further comprising:

a load sense line in fluid communication with the control port of the pressure-reducing/-relieving control valve, the pilot port of the logic element, and a load sense port of the pump, the load sense line including a check valve adapted to prevent a flow of fluid from the pump to the control valve or the logic element but to allow a flow of fluid to the pump, the load sense line adapted to

provide a load sense signal to the pump, the pump adapted to vary a flow of pressurized fluid in response to the load sense signal to generate a desired flow.

6. The hydraulic suspension system according to claim 2, further comprising:

an orifice disposed between the logic element and the chamber of the suspension cylinder.

7. The hydraulic suspension system according to claim 6, wherein the orifice is adapted to control a rate of flow of pressurized fluid to and from the chamber of the suspension cylinder.

8. The hydraulic suspension system according to claim 2, farther comprising:

a one-way restrictor disposed between the logic element and the chamber of the suspension cylinder.

9. The hydraulic suspension system according to claim 8, wherein the one-way restrictor is adapted to control a rate of flow of pressurized fluid from the chamber of the suspension cylinder.

10. The hydraulic suspension system according to claim 2, further comprising:

an accumulator in fluid communication with and interposed between the logic element and the chamber of the suspension cylinder.

11. The hydraulic suspension system according to claim 10, further comprising:

a relief valve in fluid communication with the tank and in parallel fluid relationship with the suspension cylinder, the accumulator, and the logic element and adapted such that a pressurized fluid exceeding a predetermined threshold is diverted away from the accumulator and the suspension cylinder to the tank.

12. The hydraulic suspension system according to claim 2, further comprising:

a relief valve in fluid communication with the tank and in parallel fluid relationship with the suspension cylinder and the logic element and adapted such that a pressurized fluid exceeding a predetermined threshold is diverted away from the suspension cylinder to the tank.

13. The hydraulic suspension system according to claim 2, wherein the proportional pressure-reducing/-relief valve and the logic element are combined in a single control valve.

14. The hydraulic suspension system according to claim 13, wherein the single control valve also includes a load sense check ball.

15. The hydraulic suspension system according to claim 2, wherein the suspension cylinder includes a body and a piston assembly disposed within the body and being reciprocally movable over a range of travel between a retracted position and an extended position, the piston assembly including a piston and a rod, at least a portion of which extends from the body, the body defining a piston-side chamber and a rod-side chamber, the chamber of the suspension cylinder comprising the piston-side chamber, and further comprising:

a second proportional pressure-reducing/-relief control valve interposed between the pump and the suspension cylinder and between the suspension cylinder and the tank, the second control valve in electrical communication with the controller and in selective fluid com-

munication with the pump, the tank, and the suspension cylinder, the second control valve including a spool reciprocally movable over a range of travel between at least a pump flow position in which the pump and a control port of the control valve are in fluid communication with each other and a tank flow position in which the tank and the control port of the control valve are in fluid communication with each other, the control valve adapted such that the spool moves in response to a control signal received from the controller;

a second piloted logic element interposed between the control valve and the rod-side chamber of the suspension cylinder, the second logic element in fluid communication with the control valve and in selective fluid communication with the rod-side chamber of the suspension cylinder, the second logic element including a pilot port and a poppet selectively movable between a through-flow position in which fluid can flow in either direction between the rod-side chamber of the suspension cylinder and the control port of the second control valve and a blocked position in which fluid is prevented from flowing out of the rod-side chamber of the suspension cylinder chamber, the poppet of the second logic element biased to the blocking position, the poppet of the second logic element adapted to move from the blocking position to the through-flow position when a pressure at the pilot port of the second logic element exceeds a predetermined crack pressure, the pilot port being in fluid communication with the control port of the second control valve.

16. The hydraulic suspension system according to claim 15, further comprising:

a first accumulator in fluid communication with and interposed between the first piloted logic element and the piston-side chamber of the suspension cylinder;

a second accumulator in fluid communication with and interposed between the second piloted logic element and the rod-side chamber of the suspension cylinder.

17. The hydraulic suspension system according to claim 15, wherein the controller is configured such that, once the controller receives a signal indicating that the suspension cylinder reaches a reference position or a reference pressure, the controller is adapted to control the first pressure-reducing/-relieving control valve such that the spool of the first control valve is disposed in the tank flow position such that the pressure at the pilot port of the first piloted logic element fails below the crack pressure, thereby moving the first piloted logic element to the blocked position to maintain the suspension cylinder in the reference position or the reference pressure.

18. The hydraulic suspension system according to claim 1, wherein the controller is adapted to control the pressure in, or position of, the suspension cylinder by transmitting the control signal to the proportional pressure-reducing/-relief control valve in a cyclic on-off fashion whereby adjusting the amount of time the control signal is on or off for a given time period correspondingly adjusts the pressure or position of the suspension cylinder.